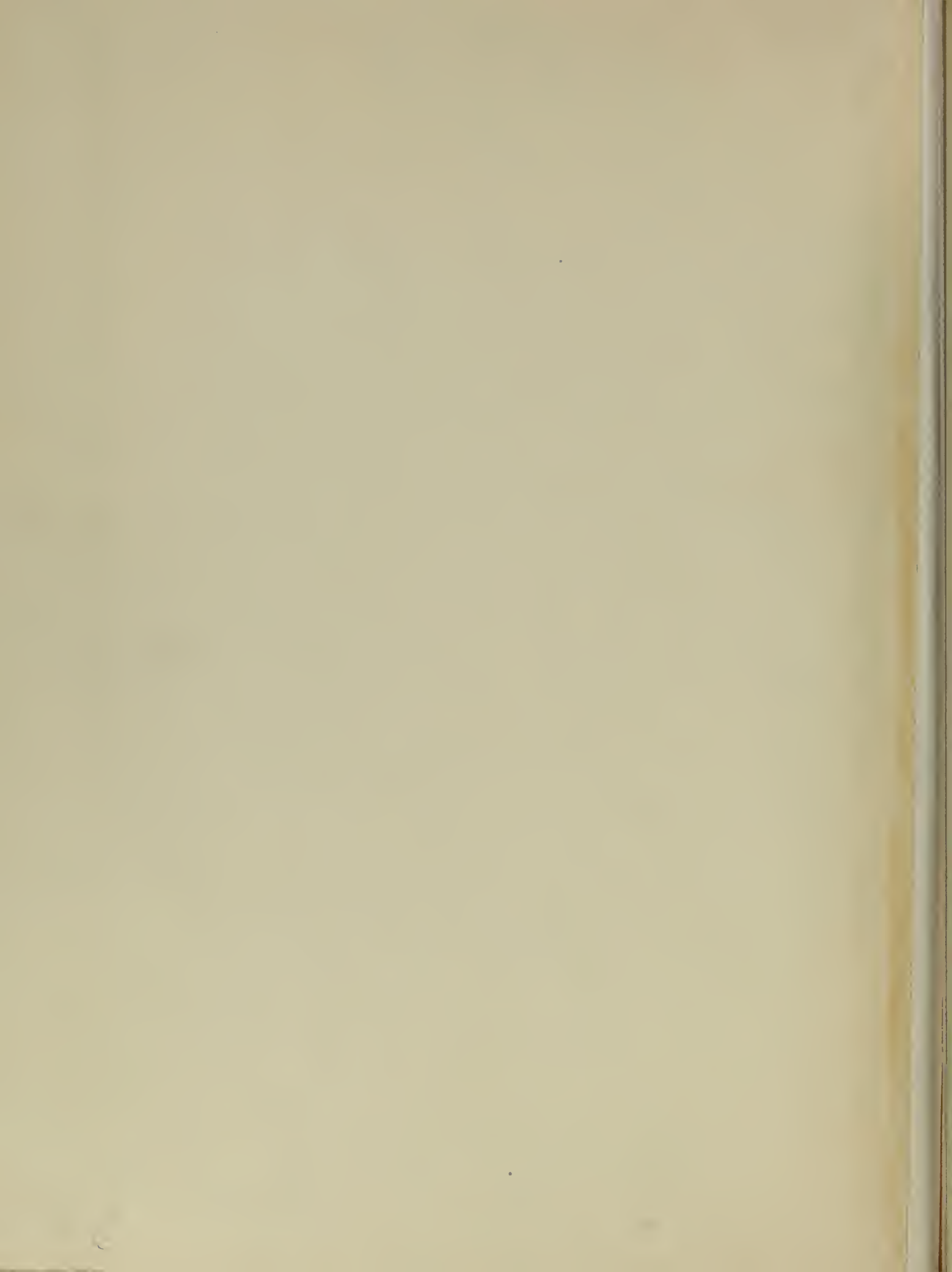


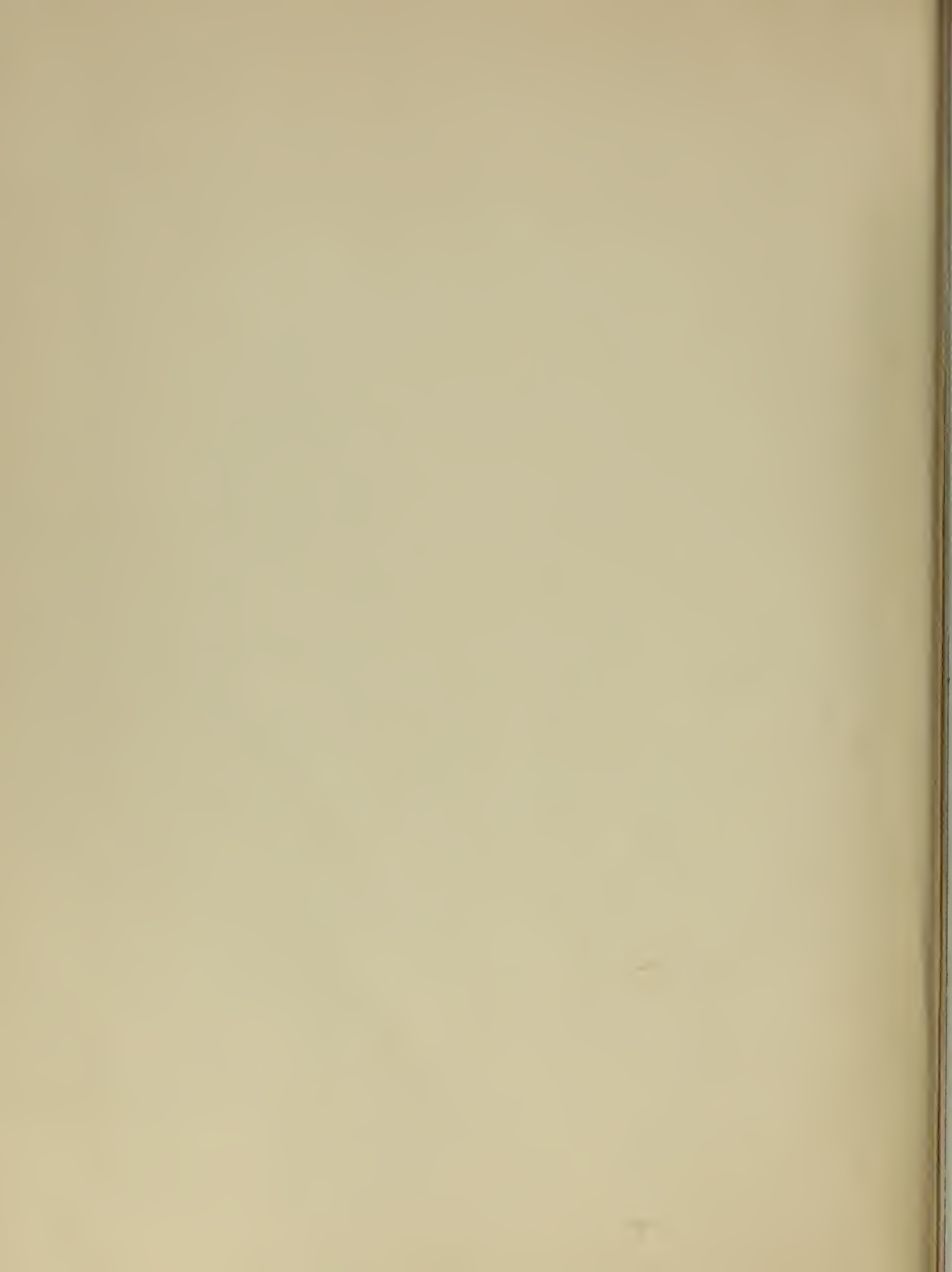
AN INVESTIGATION OF
THE USE OF INDUCTION
GENERATORS IN AIRCRAFT
ELECTRICAL SYSTEMS

BY
JOHN PEYTON HOBSON

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GENERATORS IN AIRCRAFT ELECTRICAL SYSTEMS

-

John Peyton Hobson

Thesis
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AN INVESTIGATION OF THE USE OF INDUCTION
GENERATORS IN AIRCRAFT ELECTRICAL SYSTEMS

by

John Peyton Hobson,
Lieutenant Commander, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Annapolis, Maryland
1951

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE

in

ELECTRICAL ENGINEERING

from the

United States Naval Postgraduate School



PREFACE

This paper is a theoretical investigation of the practical use of induction generators in 3 phase 400 cycle aircraft electrical systems. No particular installation was intended although the generator capacity is on the order of new machines currently being developed for use in the near future.

Since no induction motors of the power and frequency ratings desired are at present in existence such a machine was designed. However, only the electrical part of the design was considered although reasonable estimates of total weight and dimensions were necessary.

It is the author's desire to acknowledge the assistance given by Professors C.V.O. Terwilliger and W.C. Smith and to thank collectively the members and students of the Electrical Engineering Department of the Postgraduate School.

This work was performed between December 1950 and June 1951 at the United States Naval Postgraduate School, Annapolis, Maryland.

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TABLE OF SYMBOLS AND ABBREVIATIONS

AT	Ampere turns
B	Magnetic flux density
Bc	Corrected gap density
Bc1	Stator core flux density
Bc2	Rotor core flux density
Bt1	Stator tooth flux density
Bt2	Rotor core flux density
E	Voltage
f	fringing constant
H	Watts /cubic inch/ °Centigrade
I	Current in amperes
I1	Primary current
I2 = Ib	Secondary current
Iba	Average secondary current
Irm	Maximum current in end rings
Ir	R.m.s. current in end rings
K1	Slot contraction factor
Kd	Duct contraction factor
kb	Belt factor
kp	Pitch factor
l	Armature length
le	Equivalent armature length
lc	Length of end connections
N1	Number of primary conductors
N2	Number of rotor bars
Nt	Number of slots

n	Frequency
$2p$	Number of poles
p'	Number of phases
$P'h$	Hysteresis loss; watts /cubic inch
$P'e$	Eddy current loss; watts /cubic inch
$Pk2$	Total watts lost in rotor
r_1	Stator resistance
r_2	Rotor resistance
r	Total resistance ($r_1 \ r_2$)
S	Slots/phase/pole
s	Slip
T	Temperature rise, degrees centigrade
T_{ss}	Starting torque in synchronous watts
T_s	Starting torque in foot-pounds
U	Perimeter of phase belt bundle
v	Synchronous peripheral velocity
X	Total reactance ($X_1 \ X_2$)
X_1	Stator reactance
X_2	Rotor reactance
X_m	Magnetizing reactance
λ_p	Pole pitch
λ_t	Tooth pitch
δ	Radial depth of air gap
ϕ	Total flux
Δ	Peripheral current density
a_1	Equivalent stator tooth tip
a_2	Equivalent rotor tooth tip
C	Conductors per slot

d Diameter
acp Coil pitch \div pole pitch

CHAPTER I

INTRODUCTION

During the years since the beginning of World War II the electrical demand in both military and commercial aircraft has increased almost without limit. In 1940 the average load per aircraft engine was about two kilowatts while the present contemplated load today is of the order of thirty kilowatts per engine.

Up to the present day aircraft electrical systems have been primarily direct current with major emphasis being given to the twenty-eight volt system. In an effort to reduce the weight of copper conductors and to attain greater generator capacity higher voltages became necessary. And, since high altitudes make commutation and contact operation extremely difficult it was necessary to adopt an alternating current system.

This system is a nominal 208/120 volt, 3 phase, 400 cycle system. However, since the alternators are driven by the airplanes' main engines very precise constant speed drives are necessary if the alternators are to be paralleled. Such a drive is presently in use by both the United States Navy and the United States Air Force, but it weighs as much as the alternator which it drives.

This paper proposes the use of induction generators coupled to the main engines through suitable variable speed drives and connected in parallel with a constant frequency source such as an inverter. Such a system would

have the following advantages:

(1) The system frequency would be independent of generator speed.

(2) The generator speed would be determined by the load demand which is more readily sensed than frequency.

(3) The induction generator with exciting condensers is lighter than an equivalent alternator.

(4) Since an induction generator has a high rotor resistance to achieve the desired characteristics, it has a high starting torque and so can serve as the main engine starter, thus eliminating that item completely.

Induction generators, on the other hand, have the disadvantage that they will not provide any reactive power. However, it is this author's belief that the weight of copper saved will compensate for the condensers used at the loads to achieve unity power factor.

CHAPTER II

MACHINE DESIGN

Since no 400 cycle induction motors of large ratings were available with which to conduct tests, the electrical design phase of such a machine was completed. The results of this design follow:

Output	40 kw = 53.6HP
Phases	3
Terminal voltage	208
Frequency	400
Full load efficiency	0.88
Full load power factor (as motor)	0.92
Armature connection	Star
Current per phase	137.2
Number of poles	8
Synchronous rpm	6000
Gap density	
As motor	23,450
As generator	25,500
Diameter	10 inches
Length	3.93 inches
Pole pitch	3.93 inches
Induced voltage	
As motor	115
As generator	125
Total number of slots	96
Total number of active conductors	192
Active conductors per phase	64
Peripheral current density	839

Net length of iron	3.54
Fraction net iron length	0.9
Tooth pitch	0.327
Width of tooth tip	0.207
Tooth tip density	
As motor	41,200
As generator	44,800
Width of Slot	0.12
Slot opening	0.12
Section primary conductor in c.m.	25,450
Conductor dimensions	0.1 x 0.2
Insulation thickness	0.01
Depth of slot	0.5
Slot space factor	0.667
Fraction slot width	0.367

Core

Thickness of laminations	0.01
Radial depth back of slot	1.0
Maximum density	
As motor	51,200
As generator	55,600
Outside diameter	13
Volume of core (excluding teeth)	122.3
Hysteresis watts per cubic inch	
As motor	2.74
As generator	3.13
Eddy watts per cubic inch	
As motor	4.2
As generator	4.96
Total watts lost in core	
As motor	850
As generator	990

Width of tooth $1/3$ from narrow end	0.214
Max density at same point	
As motor	39,900
As generator	43,400
Volume of primary teeth	34.8
Hysteresis Watts per cubic inch	
As motor	1.84
As generator	2.02
Eddy watts per cubic inch	
As motor	2.54
As generator	3.01
Total watts lost in teeth	
As motor	152.5
As generator	175.0
Total primary iron loss	
As motor	1002.5
As generator	1165

Copper

Fraction active conductor	0.444
Length primary conductor per phase	566
Hot resistance per phase	0.0222
Primary copper loss	1255
Total Primary losses	
As motor	2257.5
As generator	2420.0

Heating

Peripheral Surface	189
Watts per sq. in. per degree cent.	0.09
Temperature rise, deg. cent.	
As motor	133
As generator	142.5
Slip at full load	
As motor	0.1
As generator	-0.1

1. The first part of the report is a general introduction to the subject of the study. It discusses the importance of the problem and the objectives of the research.

2. The second part of the report is a detailed description of the methods used in the study. It includes a description of the experimental design, the data collection procedures, and the statistical methods used for data analysis.

3. The third part of the report is a presentation of the results of the study. It includes a description of the data, a discussion of the findings, and a comparison of the results with previous research.

4. The fourth part of the report is a conclusion and a discussion of the implications of the study. It includes a summary of the findings, a discussion of the limitations of the study, and a discussion of the implications of the results for future research.

5. The fifth part of the report is a list of references. It includes a list of the books, articles, and other sources used in the study.

6. The sixth part of the report is an appendix. It includes a list of the tables, figures, and other supplementary material used in the study.

7. The seventh part of the report is a list of abbreviations. It includes a list of the abbreviations used in the study.

8. The eighth part of the report is a list of symbols. It includes a list of the symbols used in the study.

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10. The tenth part of the report is a list of appendices. It includes a list of the appendices used in the study.

Speed at full load	
As motor	5400
As generator	6600
Pulley Torque in lb-ft	
As motor	52.1
As generator	42.6
<u>Squirrel Cage Rotor</u>	
Number of slots	90
Tooth pitch	0.349
Amperes per slot	256
C.M. per ampere	174
Rotor bar section in C.M.	44500
in sq.in.	0.035
Dimensions of bar	0.1 x 0.35
Total depth of slot	0.56
Width of slot	0.12
Slot opening	0.04
Width of tooth tip	0.229
Width of tooth 1/3 from narrow end	0.214
Equivalent length of 1 bar	4.0
Total length of bars	360
Total watts lost in bars	2120
Total watts in rotor conductors	4000
Watts lost in end rings	1880
Average Amperes per bar	231
Max amperes in end rings	1300
RMS amperes in end rings	919
Total res.of end rings	.00223

Total length of end rings	59.6
Section in c.m	107,000
Section in square inches	0.084
Dimensions of end rings	.24 x .35
Secondary resistance at primary	0.285

Core

Radial depth back of slots	1.0
Maximum density	
As motor	51200
As generator	55600
Inside diameter of core	7 in.
Volume of core excluding teeth	89
Secondary frequency	40
Hysteresis watts per cubic inch	
As motor	.274
As generator	.313
Eddy watts per cubic inch	
As motor	.042
As generator	.05
Total watts lost in core	
As motor	28.2
As generator	32.3

Teeth

Max density 1/3 from narrow end	
As motor	42500
As generator	46200
Volume of rotor teeth	34.6
Hysteresis watts per cubic inch	
As motor	.203
As generator	.232
Eddy watts per cubic inch	
As motor	.029
As generator	.034
Total watts lost in rotor teeth	
As motor	8.03
As generator	9.2

Total rotor iron loss	
As motor	36.23
As generator	41.5
Total iron loss	
As motor	1038.7
As generator	1206.5
Total rotor loss	
As motor	4036
As generator	4041

Heating

Peripheral surface	194
Watt per sq.in. per degree cent.	0.148
Temperature rise	139°C

Air Gap

Radial depth of air gap	0.02
Primary tooth fringing constant	1.3
Width of primary tooth tip	0.207
Equivalent primary tooth tip	0.263
Fraction equivalent primary tooth tip	0.805
Secondary tooth fringing constant	0.6
Width of secondary tooth tip	0.229
Equivalent secondary tooth tip	0.253
Fraction equivalent secondary tooth tip	0.725
Slot contraction factor	0.584
Equivalent length of armature core	3.95
Contraction factor ($3.95 \div 3.93$)	1.005
Corrected maximum gap density	
As motor	40,000
As generator	43,500

Section 1

1. The first part of the document discusses the importance of maintaining accurate records of all transactions.

2. It is essential to ensure that all data is entered correctly and that the system is updated regularly.

3. The second part of the document outlines the procedures for handling customer inquiries and complaints.

4. It is important to respond to customers promptly and to provide them with the information they need.

5. The third part of the document describes the various services offered by the company and the benefits of each.

Section 2

6. The fourth part of the document details the company's policies on employee conduct and performance.

7. It is necessary to establish clear guidelines for all employees and to enforce them consistently.

8. The fifth part of the document discusses the company's financial goals and the strategies for achieving them.

9. It is important to monitor the company's financial performance and to make adjustments as needed.

10. The sixth part of the document describes the company's plans for future growth and expansion.

Section 3

11. The seventh part of the document outlines the company's commitment to environmental sustainability and social responsibility.

12. It is important to minimize the company's carbon footprint and to support the local community.

13. The eighth part of the document describes the company's plans for investing in research and development.

14. It is essential to stay up-to-date with the latest technology and to develop new products and services.

15. The ninth part of the document discusses the company's plans for expanding into new markets.

16. It is important to identify potential opportunities and to develop a strategy for entering those markets.

17. The tenth part of the document describes the company's plans for improving its customer service.

18. It is essential to listen to customer feedback and to make improvements based on that feedback.

19. The eleventh part of the document discusses the company's plans for increasing its marketing efforts.

20. It is important to develop a strong brand identity and to reach a wider audience.

21. The twelfth part of the document describes the company's plans for improving its internal controls.

22. It is essential to ensure that all financial transactions are properly recorded and that the company is in compliance with all applicable laws and regulations.

23. The thirteenth part of the document discusses the company's plans for improving its operational efficiency.

24. It is important to identify areas where costs can be reduced and to implement those reductions.

25. The fourteenth part of the document describes the company's plans for improving its overall performance.

25



Generated Voltage

180
 170
 160
 150
 140
 130
 120
 110
 100
 90
 80
 70
 60
 50
 40
 30
 20
 10
 0

Magnetizing Current - Amperes

Magnetization Curve
 Fig. 1

0 10 20 30 40 50



KUTVELL & LUSKE CO., N. Y. NO. 350912
10 x 10 to 100 x 100, 500 lines/cm.
MADE IN U.S.A.

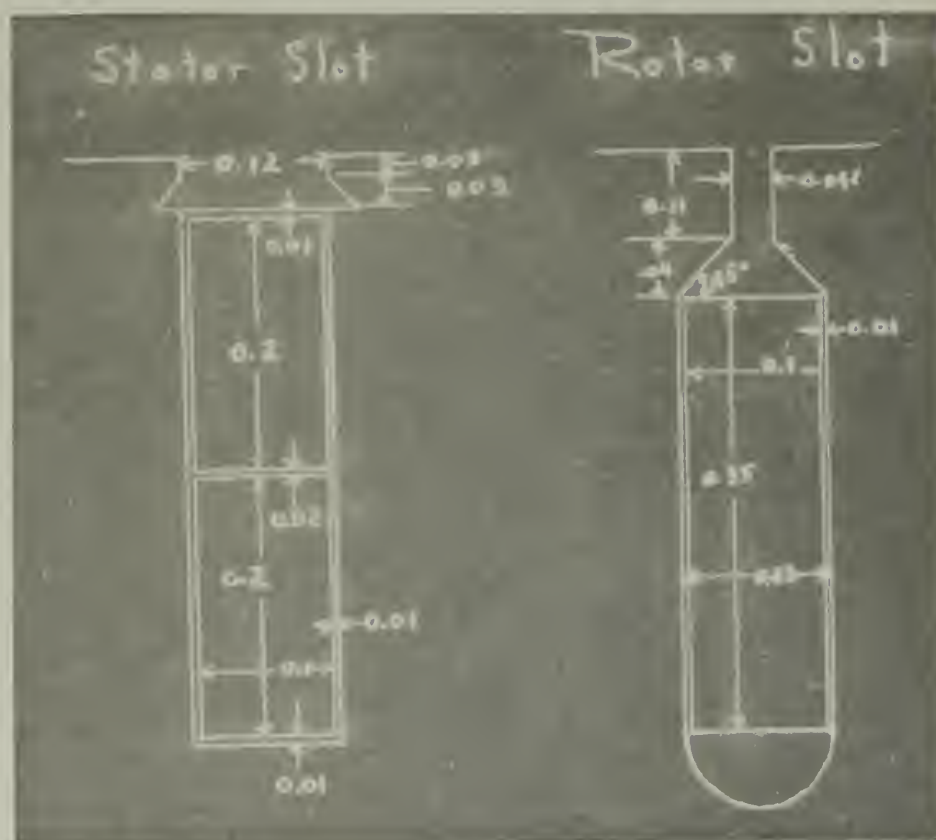
Circle Diagram
Fig. 1

Constants

Exciting reactance	4.27
Exciting resistance	35.8
Primary resistance	0.0222
Secondary resistance	0.285
Total resistance	0.3072
Primary reactance	0.0716
Secondary reactance	0.0152
Total reactance	0.0868
Leakage factor	0.0199

Breakdown and Starting

Slip at breakdown	3.18
Starting current	376
Starting torque	
Synchronous watts	120,000
Pound feet	140
Volume primary conductor	11.32 cubic inches
Volume rotor bars	12.6
Volume rotor end rings	5.01
Volume all copper	28.93
Weight all copper	9.29 pounds
Volume stator core	122.3 cubic inches
Volume stator teeth	34.8
Volume rotor core	89.0
Volume rotor teeth	34.6
Volume all iron	280.7
Weight all iron	79.7 pounds
Weight all active material	89 pounds





Weight inactive material (estimated) 9

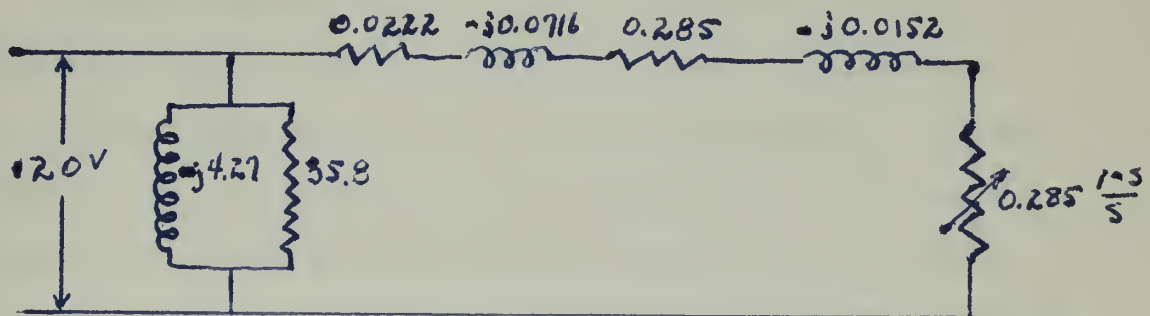
Total weight 98 pounds



CHAPTER III

PERFORMANCE

Although the important part of the circle diagram of this machine is included in this chapter (fig.2) its size precludes its use in determining the performance. Therefore, the performance of the machine as a generator has been calculated from the constants of the machine. All calculations were made using the following equivalent circuit:



For selected values of slip between -0.005 and -0.4 the current, I_{cba} , in the secondary necessary for a phase voltage of 120 volts was determined. Using this current the generated voltage was then calculated and the corresponding values of the exciting current taken from the magnetization curve.

The variable resistive losses in the rotor and stator were added to the assumedly fixed iron losses to determine the overall efficiency. The output power current is the secondary current less the fixed core loss current.

Using the exciting current, the secondary current, and the total reactance the total reactive volt amperes

required by the generator were determined.

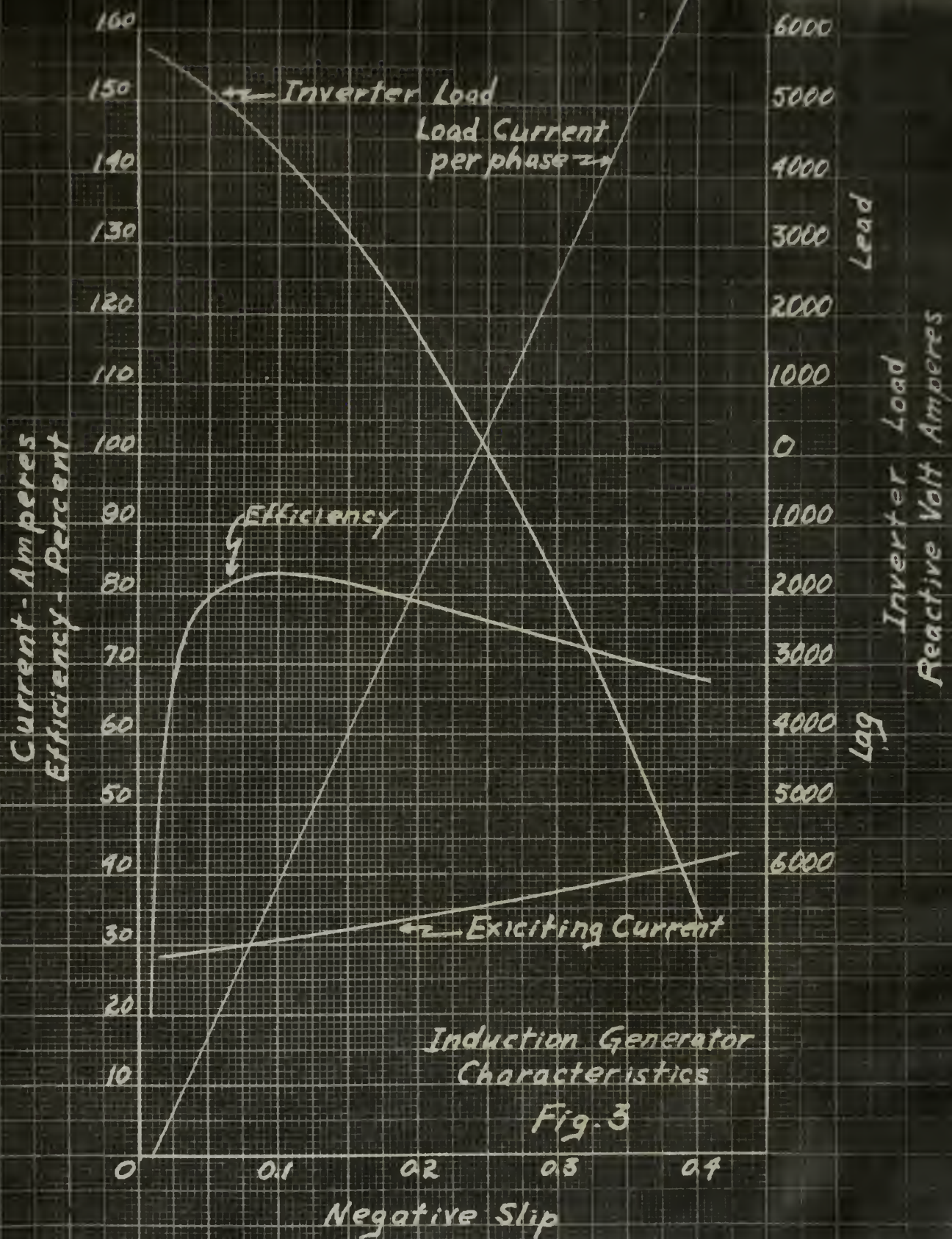
Figure 3 is a plot of exciting current, efficiency, load current per phase, and inverter load (assuming unity power factor and 85 microfarads per phase across the generator terminals) plotted against slip.

From Table III it is seen that at rated load of 111 amperes per phase each induction generator requires 16,500 reactive volt amperes in addition to the lagging reactive volt amperes required by the load.

Present Bureau of Aeronautics Standards specify 0.8 lagging power factor for all a.c. loads. This means 30,000 volt amperes for 40 kilowatts of power. In other words, if this machine is to deliver 40,000 watts some other source must provide 56,500 reactive volt amperes.

The recent advancements in the manufacture of barium titanite ceramic condensers makes their use admirably suitable for this purpose. Such condensers can now be fabricated which weigh not more than 0.03 lbs per microfarad or occupy more than 0.07 cubic inches per microfarad.

An aircraft electrical load of 40,000 watts may be reduced to unity power factor by the use of 276 microfarads of capacity which if distributed at the loads should not weigh more than 15 lbs. If this capacity is placed at the load the weight of conductor may be reduced by 20%, a reduction in weight far exceeding the weight of condensers used.





At this point, the constant frequency source must still supply 16,500 reactive volt amperes at full load and 20000 at 50% overload. If three condensers of 49 microfarads each are connected in delta across the terminals of the induction generator its requirements become 5000 VA leading at no load, zero at full load and 5000 VA lagging at 50% overload. These condensers should not weigh more than six pounds or occupy more than 11 cubic inches.

From the design of the machine it was found that as a motor this particular machine developed a starting torque of 140 ft-lbs and had a rated torque of 52.1 ft-lbs at 5400 rpm. Such a motor would be excellent for use as a starter motor for aircraft engines. The displacement of the d.c. starter motor represents a saving of approximately 90 lbs. on each engine.

CHAPTER IV

CONCLUSION

In the case of any new proposal it is desirable to compare it with equivalent equipment presently fulfilling the same purpose. Assuming a theoretical aircraft having a maximum load requirement of 40 kilowatts from each generator the following results are obtained in regard to weight:

<u>Unit</u>	<u>Alternator</u>	<u>Induction Gen.</u>
Generator	120	98
Condensers	0	21
Voltage regulator	9	0
Constant Speed Drive	75	75
Conductor	45	35
Inverter	40	120
Starter	85	0
4 KW 28 ^v d.c. supply	25	25
Batteries	<u>55</u>	<u>55</u>
Total	454	429

Although the above figures show an advantage of only 25 pounds in favor of the induction generator system, it is the author's belief that other advantages weigh even more heavily in its favor.

Since the induction generator has no brushes the problem of brush and slip ring wear at high altitudes is non-existent. The inverters necessary to the system

The first of these is the fact that the
 system is not a simple one, and that
 the results are not always the same.
 The second is that the system is not
 always the same, and that the results
 are not always the same.

Year	Population	Area
1900	1,000,000	100,000
1910	1,500,000	150,000
1920	2,000,000	200,000
1930	2,500,000	250,000
1940	3,000,000	300,000
1950	3,500,000	350,000
1960	4,000,000	400,000
1970	4,500,000	450,000
1980	5,000,000	500,000
1990	5,500,000	550,000
2000	6,000,000	600,000

The third is that the system is not
 always the same, and that the results
 are not always the same. The fourth
 is that the system is not always the
 same, and that the results are not
 always the same.

could be located in a pressurized section of the fuselage so as to reduce this problem in that equipment.

Since power is more easily sensed than frequency the control of the variable speed drive could be simplified. Small variations in generator speed will produce changes in load distribution but no circulating currents will exist unless a machine drops to or below synchronous speed.

The induction machine being basically a simpler more rugged machine than the synchronous type it should be both cheaper to build and more durable in service.

APPENDIX

The following formulae were used in the design of this machine:

$$E = 8.06 \text{ kbkpVlNB } 10^{-8}$$

$$\Delta = NI \div \pi d$$

$$\lambda_p = d \div 2p$$

$$\lambda_t = d \div Nt$$

$$Ph' = 2 \frac{n}{100} (Bm^{10^{-5}})^{1.6}$$

$$Pe'' = (n Bm t 10^{-5})^2$$

$$l1'' = 1 + 1.5 Acp \lambda_p$$

$$H1 = (1 + 0.02v) \div 60$$

$$T1 = P1 \div H_1 S_1$$

$$Pk2 = 7465 \text{ HF} \div N$$

$$\Delta = 1.23 \cdot 10^{-8} \div kp \text{ Bd}^2 l$$

$$Ib = 1.01 \Delta \lambda_{tL}$$

$$Iba = Ib \div 1.11$$

$$Ir = Nt2 \cdot Iba \div 4 \cdot 2 P$$

$$r_2 = Pk2 \div (I \eta \text{ p.f.})^2$$

$$f = 0.6 + 1.47 \log (Sol \div 2)$$

$$t1 = tt1 + 2 f \cdot \delta$$

$$a1 = t1 \div \lambda_{t1}$$

$$a2 = t2 \div \lambda_{t2}$$

$$K1 = A.A2$$

$$le = 1 + \delta - Nd (Wa - 2fd) = 1 + \delta$$

$$Kd = le \div 1$$

$$Bc = B \div K1 Kd$$

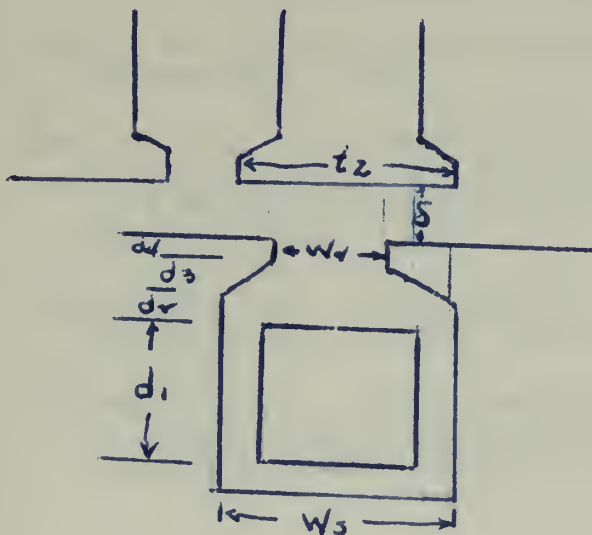
$$ATg = 0.626 Bc \delta$$

$$\chi_1 = 2\pi \times 10^{-8} k p k p S_1 C_1^2 N \phi_1 l$$

$$N \phi_1 = 3.19 \left[\frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4 + w_3} + \frac{d_4}{w_4} \right] + 3.19 \frac{t_2 - w_4}{6s} + \frac{l_c}{2} \left[.146 \log \frac{\pi k}{u} + 0.064 \right]$$

$$\chi_2 = 2\pi \times 10^{-8} k p k p S_2 C_2^2 N \phi_2 l \left[\frac{C_1 S_1}{C_2 S_2} \right]^2$$

$$N \phi_2 = 3.19 \left[\frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4 + w_3} + \frac{d_4}{w_4} \right] + 3.19 \frac{t_1 - w_4}{6s} + \frac{l_c}{2} \left[.146 \log \frac{\pi k}{u} + 0.064 \right]$$



p = no of poles

S = slots /phase/ pole

C = conductors/slot

U = perimeter of phase belt bundle

lc = length of end connections

$$I_s = E \div \sqrt{r^2 + x^2}$$

$$T_{ss} = p' I_s^2$$

$$T_s = 0.117 p T_{ss} \div n$$

مجلس شورای ملی

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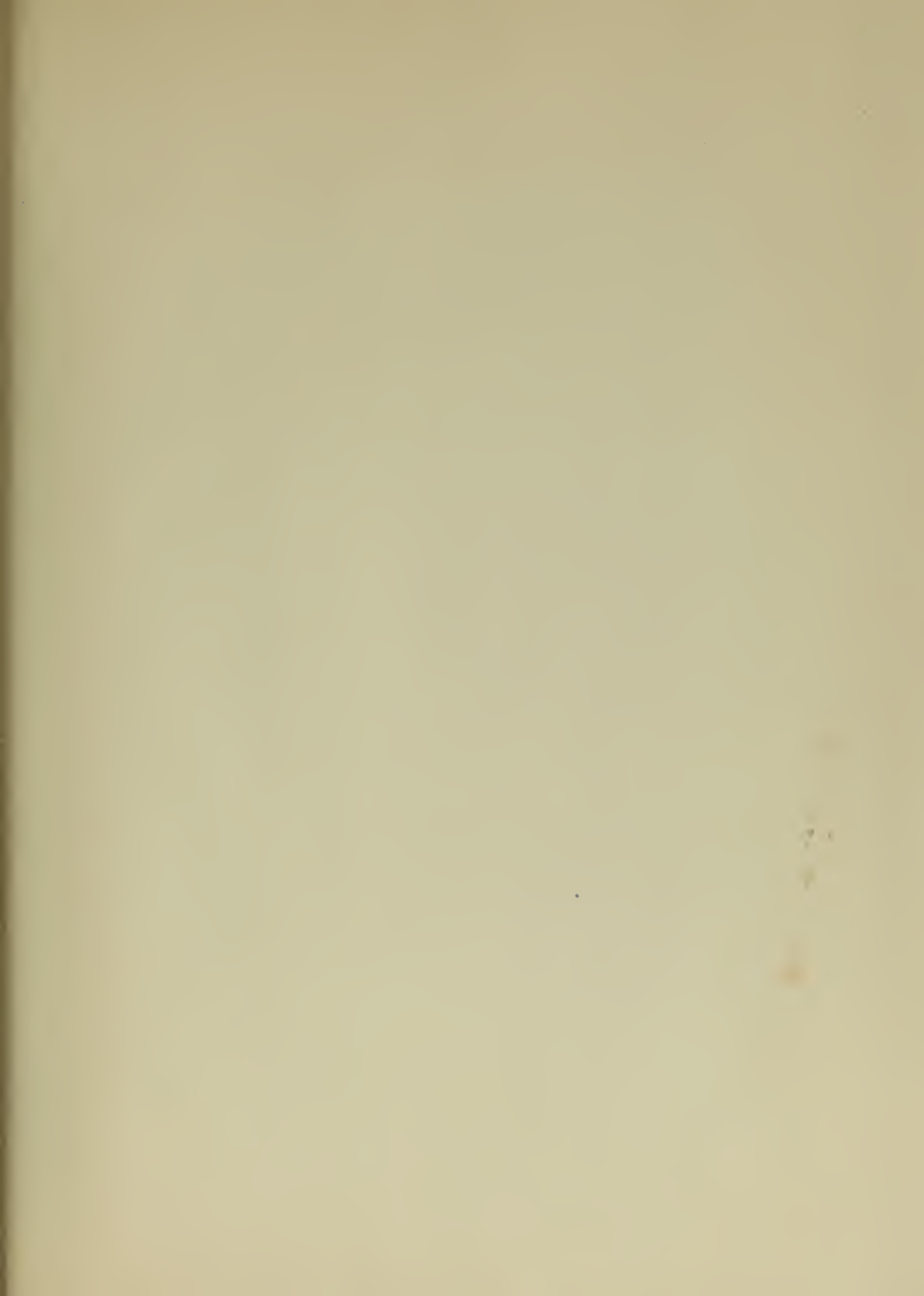
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use of induction generators
in aircraft electrical systems

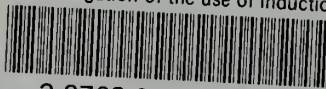
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